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Low cost stove-top thermoelectric generator for regions with unreliable electricity supply

R.Y. Nuwayhid [a,*], D.M. Rowe [b], G. Min [b]

[a] *Department of Mechanical Engineering, Faculty of Engineering and Architecture, American University of Beirut, Riad El Solh 1107-2020, Beirut, Lebanon*

[b] *NEDO Thermoelectric Laboratory, Electronic Engineering Department, Cardiff University, Cardiff, Wales, UK*

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Abstract

During the winter months in regions where constant electric power supply cannot be relied upon, power may be derived parasitically from heating stoves. A proportion of heat from these 20–50 kW wood or diesel-heated stoves may be utilized to drive a thermoelectric generator (TEG) consisting of several commercially available low-cost modules. These are Peltier modules operating in a power generating mode and adapted to the low-flux regime coupled with hot side temperatures of 100–300 °C. Two commercially available modules are considered. The generator is then theoretically re-evaluated with the Peltier modules re-designed in order to produce maximum power in a simple and cheap manner allowing easy commercial production using existing technology. A current power target is set at 100 W for a minimum domestic use.

Keywords: Thermoelectric power; Stove-top; Waste-heat; Optimized design

1. Introduction

In some areas in the developing world, electric power supply is unreliable and may be intermittent. The reasons for this depend on the particular area. In many cases it can be attributed to shortages of spare parts for conventional power plants, poor engineering and maintenance, and in some cases loss of electric power transpor-

* Corresponding author.
E-mail address: rida@aub.edu.lb (R.Y. Nuwayhid).

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Nomenclature

A	Area of thermoelement (mm^2)
A_m	Area of module (mm^2)
a	spacing between thermoelements within module (mm)
C	A constant
D	side-length of a square module (mm)
F	Manufacturing Quality Factor
L	Length (also termed height) of thermoelement (mm)
L_C	Length (thickness) of solder/contact in module (mm)
N	Number of thermoelements per module
n	Contact parameter ($=2\rho_c/\rho$) (mm)
P	Power (W)
r	Contact parameter ($=\lambda/\lambda_c$) (dimensionless)
T_H	Temperature of heat source (K)
T_C	Temperature of heat sink (K)
x	side length of a square thermoelement (mm)
Z	Thermoelectric figure of merit ($=\alpha^2\alpha/\lambda$) (K^{-1})

Greek symbols

α	Thermoelectric material Seebeck coefficient (V/K)
ρ	Electric resistivity of thermoelectric material (Ω.mm or Ω.cm)
ρ_c	Contact electric resistivity (Ω.mm or Ω.cm)
λ	Thermoelectric material thermal conductivity (W/cm.K)
λ_c	Contact thermal conductivity (W/cm.K)
σ	Thermoelectric material electric conductivity (e.g. $\Omega^{-1}.cm^{-1}$)
ϕ	Thermodynamic efficiency

tation lines. Of course, civil unrest and/or war are a common theme and may in many cases be the overlying cause of the power failures. In areas such as these, and in particular the more rural parts, it is common to find wood or diesel fired stoves. As an example, in the mountain towns and villages of Mount Lebanon, these stoves are used during the winter mostly for room heating and occasionally for cooking. The stoves are assembled with the onset of the cool-rainy season in October and remain in place until about May. Such a scene, coupled with frequent electric power supply failures, makes the proposition to introduce stove-run thermoelectric generators possibly feasible. Main requirements would have to be low cost, reliability, simplicity, and the capacity to generate a minimum acceptable power.

Recently a woodstove-thermoelectric system was proposed for rural extreme north Sweden [1]. While the weather on Mount Lebanon is far milder in winter than in

Sweden, it must be noted that the common theme is either the total absence (north Sweden) or the undependability and unpredictability (Mount Lebanon) of the electric grid. While photovoltaics (PV) is a valid option in the Lebanon case with extended winter sunshine periods, it requires more maintenance and cleaning and is 'on-the-roof' as opposed to the TEG which is sitting in front of the user on the stove! Furthermore, sunshine may not be available when most needed when there is a prolonged power failure coupled with extended bad weather. An ideal system may be a combined PV–TE unit such as studied in [2], although this is bound to be limited to a somewhat larger-scale user due to complexity and cost.

The thermoelectric technology currently available is very promising. Research at Cardiff University NEDO Thermoelectric Engineering Laboratory has made some progress notably in maximizing module power output and in identifying new low-cost materials with good performance. Typical of these is the High Power Density Generator (HPDG) module developed at Cardiff, which produces several times the power output per area of technologically similar commercial modules using bismuth telluride. Additionally, work on magnesium–tin based materials, which are cheap and exhibit large power factors ($\alpha^2\sigma$), is progressing.

When using appliances such as woodstoves, surface temperatures are likely to be in the range 150–350 °C (420–620 K). Commercially available thermoelectric Peltier modules usually are limited in operation to below about 80 °C (350 K) by the contacting solder melting point, although there are some Peltier modules which are claimed to operate safely and continuously up to 160 °C (450 K) (e.g. Melcor's HT6 module). Making use of Peltier modules for power generation has been proposed by Rowe and Min [3]. While the available heat source may be at a higher temperature part of the time, there would have to be some 'attenuation' if the Peltier modules, rather than more expensive custom-built PbTe or SiGe devices, were to be used. Another option is to use so-called type-II bismuth telluride based modules specifically designed to withstand operation up to about 230 °C. Hi-Z/USA (e.g. HZ-20 module) and more recently NPP-Biapos/Russia (e.g. ND-18 module) manufacture are examples of these modules. These modules are larger in size, have no insulating layers at the hot and cold ends, have insulation between their thermoelements, and produce more power per module mostly due to the large thermoelement size, but at a cost from $150–220 per module. A point to assess when considering type-II modules is that while they may operate at up to 230 °C, a ΔT of over 140 K is difficult to achieve practically and thus the use of these modules may be less attractive compared to the cheaper type-I (Peltier) modules.

When fuel is at a premium (costs money), then efficiency is the dominant factor as is the case in large-scale power generating systems. Consequently if a thermoelectric generator were to be used, materials with a large Z would be required. At the other extreme, when the heat supply is unlimited and may be regarded as free (or nearly so) as is the case of waste-heat or 'parasitic' heat recovery, large power factors ($\alpha^2\sigma$) become the overriding requirement [4]. While the two limiting cases are well defined, there exists a region borderline between the two. In this domain, the heat supply may be virtually free (waste-heat) but limited in amount. The heat flux available

may be low or borderline to what may be required for optimum operation of a given thermoelectric module.

This work will consider the thermoelectric recovery of power typical of rural domestic woodstoves. Pertinent thermoelectric equations will first be presented. These will be modified for maximum power performance, and used to optimize the geometrical aspects of several thermoelectric module designs. Simple cost considerations will be discussed in order to pave the way for the advance of in-situ thermoelectric power generation at the domestic user end.

2. Theoretical background

2.1. Power output and efficiency

The required power for the application considered in this paper is that it is sufficient to run a small television set and light two or three low wattage lamps. A general target is taken to be 100 W or thereabouts.

Theoretically, the maximum power output of a realistic thermoelectric module taking into account contact resistances is given by [5]:

$$P = \frac{\alpha^2\sigma}{2}\frac{NA}{(L+n)(1+2rL_C/L)^2}(T_H-T_C)^2 \tag{1}$$

Typically, $n = 2(p_c/p) = 0.1$ mm, $r = \lambda/\lambda_c = 0.2$, and the alumina wafer thickness maybe $L_c = 0.8$ mm. A typical value of $\alpha^2\sigma = 37\times10^{-4}$ W/m.K^2 can be used for Bi_2Te_3-based modules which is an average value in the range from 50 °C to about 150 °C. For a typical Peltier module L may vary from about 2.2 mm to about 1.2 mm. For such a module with 127 couples, a thermoelement area of 1.96 mm^2, and a temperature drop of 100 K something between 1.5 and 2.5 W per module may be ideally expected. The thermoelement length for obtaining maximum power output may be found by differentiating the above relation with respect to L (since all other parameters are constant for a given selected material and operating condition. The corresponding optimum length is found from taking $\partial P/\partial L = 0$. This gives: $L^3-0.62L^2-0.096L-0.0032 = 0$ which, for the case at hand gives $L_{opt}\approx0.4$ mm.

In addition to obtaining maximum power per module, it may be thought appropriate to minimize the area of the proposed generator by considering cascading (2-stage). The problem with this is that, for a given (fixed) overall temperature difference, less power will be obtained then in a single stage case and consequently there is no justification for cascading.

Efficiency, is given by [5]:

$$\phi = \frac{(T_H-T_C)}{T_H}\left\{(1+2r\frac{L_C}{L})^2\left[2-\frac{1}{2}\left(\frac{T_H-T_C}{T_H}\right)+\frac{4}{ZT_H}\left(\frac{L+n}{L+2rL_C}\right)\right]\right\}^{-1} \tag{2}$$

The power versus efficiency behavior is shown in Fig. 1 and it is evident that the highest power would be at a reduced efficiency. The selected design point would be

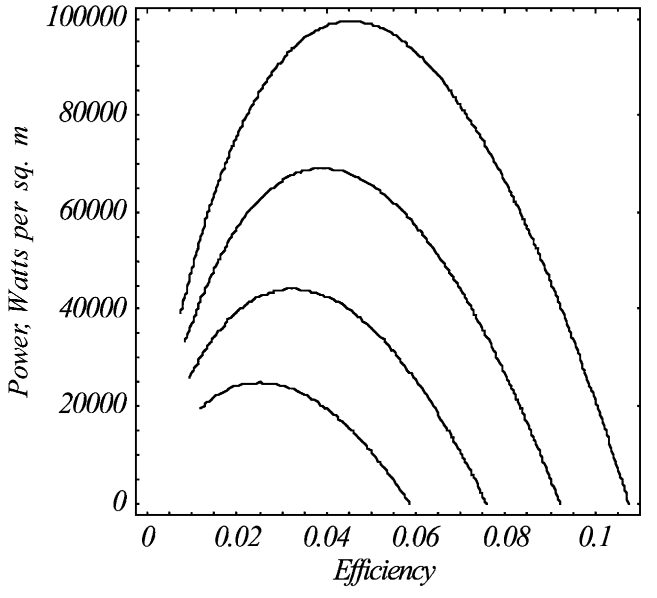

Figure 1. Power (at matched load) per unit area per thermoelement versus efficiency for a typical bismuth telluride Peltier type module. From top to bottom ΔT is 300, 250, 200, and 150 K. T_C = 300 K.

somewhere in the range between maximum power and maximum efficiency where the available heat crossing the device is actually being converted. Here, it should be recalled that the quality of the source heat must be assessed. With waste-heat, maximum power becomes the prominent goal. At the other extreme, when high-quality prime fuels are being used to supply heat, efficiency is the overwhelming consideration. The previous consideration is what drives this work.

2.2. Optimizing power by length reduction

It is evident from eq. (1) that a reduction in the leg length would lead to an increase in power output (for a given leg area). In fact there is an optimum leg length dependence on the other parameters of the equation. Rowe [6] successfully re-designed a typical Bi_2Te_3 module with reduced leg length, closer leg distances (i.e. larger leg areas) and obtained measured power outputs up to 4 to 5 times as high as the commonly available Peltier modules of comparable overall surface area.

With a low-cost commercially available Peltier module, it is possible to re-design for increased power. It has been shown [7] that maximum power is achieved at a length which is dependent on the temperature difference and is optimized at quite short lengths. Efficiency, on the other hand, is highest at large leg lengths. Practical design requires a compromise between maximum power and maximum efficiency.

Eq. (1) can be written as:

$$P = FN\Delta T^2\left(\frac{\alpha^2\sigma}{2}\right)\left(\frac{A}{L}\right) \tag{3}$$

where, following Rowe and Min [5], F is the Manufacturing Quality Factor (MQF) which incorporates the contact and geometrical aspects of the module and is given by:

$$F = \frac{1}{(1 + n/L)(1 + 2rL_C/L)^2} \tag{4}$$

If the leg length were to be changed (reduced), the expected change in the MQF assuming simple contact characteristics is:

$$\Delta F = \frac{F'}{F} = \frac{(L + n)(1 + 2rL_C/L)^2}{(L' + n)(1 + 2rL_C/L')^2} \tag{5}$$

,where the prime indicates the new (reduced) length. This equation can be used to compare amongst modules.

It is apparent from eq. (4), an increase in MQF will result in an increase in power. For a typical module, reducing the length from the commercial size of about 2.2 mm to about 1.6 mm, results in a power increase of some 21%. This calculation assumes similar α, ρ and $(T_H - T_C)$ and is not exact since the temperature drop will change which will, in turn, affect the other parameters. In practice, a slightly smaller gain should be expected unless strict control of ΔT were possible.

Thus to optimize performance a leg length would be selected somewhere close to the maximum power point but on the increased efficiency side. This is so because, while the heat input is ‘free’, too low an efficiency would mean that very little of the heat crossing the device is converted. This, in a ‘borderline’ regime (as mentioned above) is unacceptable.

2.3. Dependence of optimum power on module geometry

Optimization of the thermoelement leg length depends on the contact properties n, r, and L_C (eq. (1)) that vary somewhat among module designs but can be treated as nearly constant. If the module size was pre-selected, a further optimization may result which is dependent on the number of couples that could be packed in the module, the leg cross-sectional dimension, and the inter-leg spacing.

For any module area (A_m), leg length (L), leg square side width (x), and inter-leg spacing (a), the maximum power equation can be rewritten as:

$$P_{\max} = F.\left(1 + \frac{2a}{x} + \left(\frac{a}{x}\right)^2\right)^{-1}.\Delta T^2.\left(\frac{\alpha^2\sigma}{4}\right).\left(\frac{A_m}{L}\right) \tag{6}$$

where the relation uses the fact that if the module side length is D, then the number of couples is $N = \frac{1}{2}\left(\frac{D}{x + a}\right)^2$, and the module area is obviously D^2. To use the above equation, the module size, operating range and material must first be selected. Given the contact properties and leg height, the manufacturing quality factor (F) is determined. The selection of appropriate leg square side width (x) and inter-leg spacing (a) then follows.

To illustrate the L–x–a relationship using Bi_2Te_3 properties typical of the temperature range of operation (50–150 °C) and an achievable ΔT of 100 K, the maximum power (in W) can be put in the form:

$$P_{\max} = 0.00925D^2 \frac{x^2}{(x + a)^2(L + 0.1)(1 + 0.32/L)^2} \tag{7}$$

For a given module size (D) and inter-leg spacing (a), Fig. 2 shows the maximum power to be dependent on the amount of material can be packed into the module and on the aspect ratio of the thermoelement leg (x/L). It is observed that maximum power peaks at increasingly smaller leg heights as the leg width (and area) increases. Squat film type elements would thus be preferable over long slender wire type elements for power generation. Below the optimum leg height however, power drops and more abruptly so for the film type elements due to incipient 'film' resistance.

To show the effect of the inter-leg spacing, Fig. 3 is presented as maximum power versus leg height for two cases: $x/L = 1.0$ (typical of current Peltier modules) and $x/L = 5.0$. A clear increase in power results from reducing the spacing for a given leg height (and width since they are related here). With the larger size legs the increase becomes significant. Practical considerations however, would not allow a decrease of inter-leg spacing below about 0.5 mm and at such spacing a switch to type-II modules becomes necessary.

It is noted that there exists some room to optimize the Peltier-type modules for power generation. A possible design goal could be to first retain a given module size such as the standard 40x40 mm module provided by many manufacturers. The inter-leg spacing may be set at 0.7 mm out of practical limitations such as manufac-

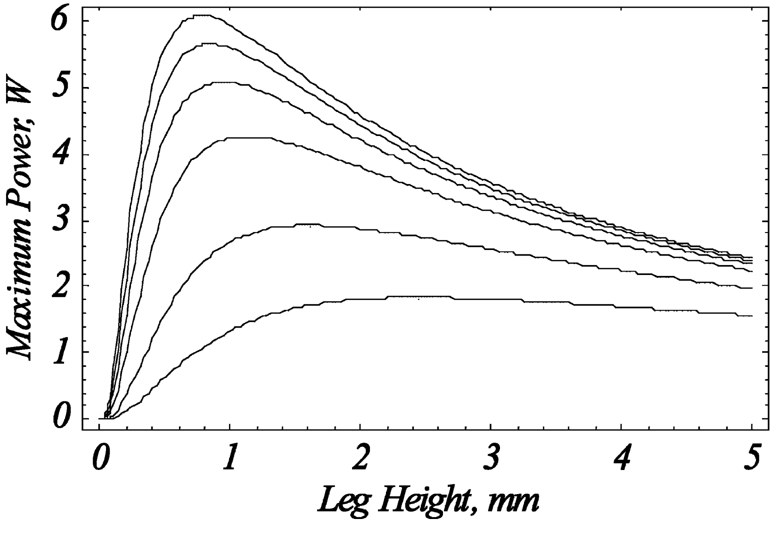

Figure 2. Maximum power versus thermoelement leg length (height) for several leg (square) widths. The module size is 40 mm x 40 mm and the inter-leg spacing is set at 0.7 mm. The curves from top to bottom are for x/L= 5, 4, 3, 2, 1, and 0.5 respectively.

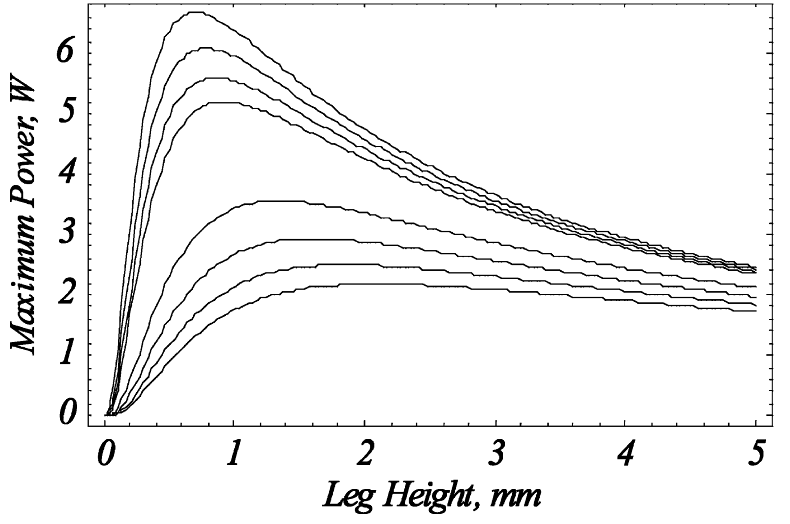

Figure 3. Effect of inter-leg spacing on maximum power behavior. Two sets of curves; lower set is for $x/L = 1$; upper set for $x/l = 5$. For each set the inter-leg spacing increases from top to bottom as 0.5, 0.7, 0.9 and 1.1 mm.

turing ease and prevention of possible short-circuiting. The leg-height/leg-width ratio may be selected with some freedom but it is clear that large values are better. The number of couples would be few if the area to height of the legs were too large.

3. Materials and methods

3.1. Stove specifications, heat input and temperature

There is no standard design of a stove. Two types are employed: wood and diesel fed. Even within these two types there are several quite different models. The proposed TEG should be suitable for use with all types of room heating stoves. A stove-top design would thus be most appropriate and would need no special attaching to the stove. To proceed one type of commonly available wood-fired stove is considered. Such a stove/heater has dimensions approximately 60x50x40 cm (length, width, and height) with a volume of about 0.1 m^3 and surface area about 1.5 m^2. The material is cast iron with side doors to feed the wood chunks. The top is about 1.5 cm thick and has removable rings. The exhaust fume stack is on one side at the back and is normally erected vertically and through the ceiling to the roof.

Considering a typical usage of the stove with average heating values for wood of 15,000 kJ/kg, it is estimated that the instantaneous heat input rate might be in the range 10 to 50 kW. The large difference is due to the irregular feeding rate followed. For the same reason, the stove-top temperature will not be quite steady and non-

uniform. Fig. 4 shows the actual temperatures on the stove-top in a real situation. Thus, the surface temperature may fluctuate over time between a maximum of about 300 °C and a minimum of around 50 °C depending on the part of the stove considered. Of course, the location chosen for the generator would have to be chosen based on allowable temperatures and on practical considerations. Positions A, B or C (or somewhere between them) would seem most appropriate. The power output from the TE device will vary and certain measures may need to be taken to control the effect of this fluctuation on the device in future work.

Based on the heat input, neglecting heat losses, and with a module surface area of about $1.6x10^{-3}$ m^2, the heat flux across it may be in the range 7 to 33 kW/m^2. The average heat flux in the module is 20 kW/m^2 (2 W/cm^2), which is slightly on the low side of accepted waste heat candidate applications. It may still be possible to make the best use of the heat source by incorporating battery charging during a low use period of stove operation. Inclusion of batteries and associated equipment, however, may not readily be justifiable on cost grounds.

Estimating the thermal conductance of the TE module (including alumina plates) to be around 0.3 W/K, the temperature difference expected across it would be in the range 40 to 175 K depending on the stove-top flux output. With an average ΔT of 100 K, this is consistent with the selection of commercially available modules producing around 1 Watt in that regime (i.e. 20x1000x0.0016/0.3 = 106 K).

As an alternative, as mentioned previously, small diesel stoves/heaters are increasingly being used in the area being considered. The approximate (minimum) fuel usage is about 10 l/day. This translates into a heat rate of about 25 kW, which is in the same range as has been discussed for the woodstoves.

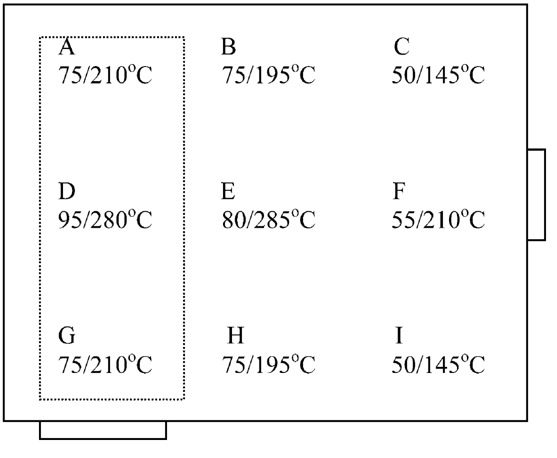

Figure 4. Stove-top surface temperatures. Shown are minimum and maximum recorded temperatures during a 30 minute run from just after startup until steady burning. The bottom side box is the charging door, while the right side box is the exhaust duct. The broken line is the location of the firebox within the stove. The fumes rise to the right towards the exhaust duct under positions E and F.

3.2. Thermoelectric material/module selection

In general thermoelectric modules for public use must fulfil a number of criteria: (1) A high Z value, (2) Stability, and resistance to oxidation, sublimation, and evaporation, (3) Good contact properties, (4) Non-toxicity, (5) Low component cost, and (6) Simplicity of design.

When considering a waste-heat ‘Parasitic’ application, the primary criterion is a high power factor ($\alpha^2\sigma$). Optimization requires a high power factor even at the expense of reducing Z to some extent. With that in mind and given that the maximum temperature available on the stove surface is about 300 °C (550 K), the options to be considered include:

- Iron disilicide ($FeSi_2$). This has excellent stability at high temperatures and may be used in open flames. The power output is, however, too low to make this an interesting preposition [8]
- Lead telluride (PbTe). But this offers no advantage in this temperature-limited regime. In fact in this range Bi_2Te_3 has an advantage in both power factor and Z as well.
- Use densely packed large area modules based on Bi_2Te_3 (e.g. Hi-Z). These are the foremost possibility currently. These may suffer somewhat from contact inadequacy leading to some power loss and could use some re-design for more power. They are limited to a maximum temperature of 230–250 °C leading to a loss of some available heat (up to 300 °C). They appear costly per module at first.
- Use so-called high-temperature Bi_2Te_3 Peltier cooling modules in a power-generating mode (e.g. Melcor HT6 among others). These suffer from optimization inappropriate for power generation. Additionally, being limited to a maximum hot temperature of about 170 °C requires significant attenuation and heat availability loss. While here the advantage in power factor over PbTe material is reduced (due to attenuation), it still exists.

As already shown, maximum power will be obtained when the thermoelement leg is of optimum length. For commercially available Peltier modules, the leg lengths are longer than optimum (being optimized for cooling rather than power). In the power generating modules, the leg area-to-height ratio is much larger (i.e. 5 versus 1).

In the borderline waste heat regime being considered (having eliminated PbTe technology), the choices available are:

- Use available power modules (Hi-Z HZ-20, NPP-Biapos BT-18/4 ...) based on bismuth telluride.
- Custom manufacture Bi_2Te_3 modules.
- Use available Peltier Bi_2Te_3 modules in the generating mode (Melcor HT6 …)

Based on the above, three cases will be discussed:

1. Design based on existent high temperature Peltier modules.

2. Design based on re-designed high-temperature Peltier modules.
3. Design based on Hi-Z, HZ-20 modules (or similar NPP-Biapos modules).

4. Practical module design

4.1. Temperature profile through module/generator

A simplified model of the generator was modeled using a 2-dimensional heat transfer program. Fig. 5 shows a half-section of the generator model. The program assigns appropriate thermal conductivities to each material section as well as a convective heat transfer boundary condition to the top side. Typical values were used for the materials such as aluminum, insulator, steel screws, bismuth telluride, and alumina. The conductive coefficient was typical of forced air convection.

Fig. 6 shows the temperature profile through a section of the generator from the hot plate to the fin base. It is seen that the fixing screws present a significant heat leak path thus causing cold side temperatures to be high (and a resultant low ΔT). In reality, the situation is not as bad as presented in the figure since the model is only 2-dimensional and it does not show the situation deeper within the generator.

4.2. High-temperature Peltier module design

To illustrate the present state of technology, Table 1 gives some characteristics of some commercially available modules of both the Peltier type-I and power type-II designs (this is a partial list and there exist several more excellent Peltier modules).

The table shows that the Chinese manufacturers can deliver modules at the best

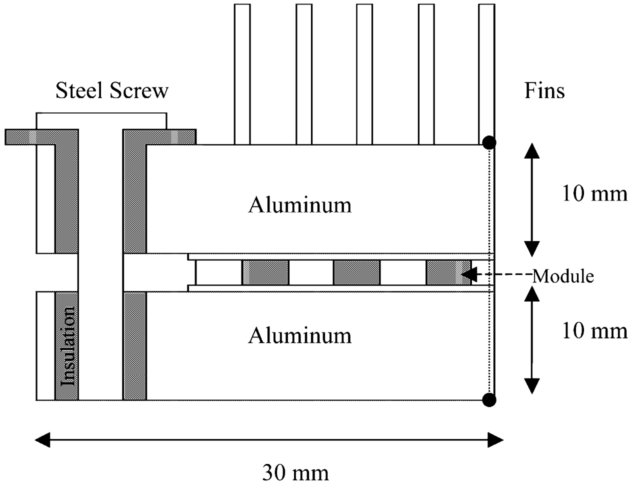

Figure 5. Model of single module generator test rig. Half the generator is seen and the view is at slice through the edge of the rig through the fixing screws. Dark parts are insulation.

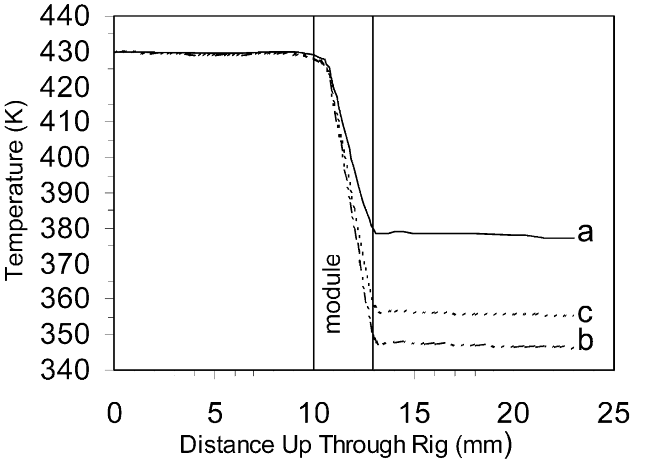

Figure 6. Temperature profile through center of single module generator from hot side via module to fin base. Convective coefficient $h = 100$ W/m^{2}K. (a) Aluminum screws and nuts with no insulating gasket above it. (b) Steel screws and nuts with an insulating gasket above it. (c) As in (b), but convective coefficient is 75 W/m^{2}K.

Table 1
Characteristics of some commonly available commercial Bi_2Te_3 modules

	HT6-12-40 (Melcor, USA)	TEC1-12708 (China)	HZ-20 (Hi-Z, USA)	NPP/Biapos (BT-18/4) (Russia)
Leg length x width (mm x mm)	1.35 x 1.35	1.4 x 1.4	5.0x5.0	5.0 x 5.0
Leg height (mm)	1.6	1.2	4.5	6.0
Contact/solder height (mm)	0.6	1.0	–	–
Insulator plate thickness (mm)	0.8	0.63	None	None
Module height (mm)	3.8	3.46	5.0	8.5
Inter-leg spacing (mm)	1.0	1.1	Insulated(0.1-0.2?)	Insulated(0.1-0.2?)
Area-to-length ratio	1.14	1.63	5.55	4.17
No. of couples per module	127	127	71	83
Maximum operating hot side temperature (°C)	160 - 170	160 - 170	230	270
Module cost ($)	22	8	200+	150

price. The power modules are clearly seen to be costly. The module HT6-12-40 (Melcor, USA) and the module TEC1-12708 (Taihuaxing, China) were selected for the base study. Using the specifications of these modules as given in Table 1, the maximum theoretical power is given by eq. (7) as:

$$P_{\max} = C \times 10^{-4}\Delta T^2,\mathrm{W} \tag{8}$$

where C is 1.75 for the HT6-12-40 module and 2.40 for the TEC1-12708 module which is numerically the power output of the modules in W if the temperature difference is taken to be 100 K. The larger output of the second module is clearly attributable to its shorter legs (and also larger cross-sectional area). This treatment is a little more realistic than is found in some manufacturer catalogues that tend to neglect the contacts effect.

Using the expected powers, the minimum number of modules for a 100 W target application is found to be 56 and 42 using the HT6 or TEC1 modules respectively. For simplicity the number of modules is rounded up to the next highest number that gives a square layout thus becoming 64 and 49 modules for each type.

The side dimension of a generator incorporating these number of modules would be about (see table for module size) 32 cm or 28 cm. The cost of the modules alone would be \$1400 or \$400 for the two types respectively. The volume of the whole generator would be around 0.015 m^3 and 0.01 m^3 for the two types giving a power density of about 6.7 kW/m^3 or 10 kW/m^3 respectively. This is a rather low achievement compared to current goals of achieving around 50 kW/m^3 at the NEDO Laboratory, Cardiff [6]. The cost can be expected, assuming for simplicity a 25% materials and manufacturing cost, to be something like \$17/Watt or \$5/Watt for the HT6-12-40 and TEC1-12708 modules respectively. The Chinese module TEC1-12708, due to the low cost, is clearly worth developing. Reliability, however, is something that must be considered as well.

4.3. Current technology module performance

An immediate application would probably require the use of available Peltier modules. The HT6-12-40 module from Melcor (USA) or the TEC1-12708 module from Taihuaxing (China) are considered since these are capable of operation at up to and a little over 160 °C. For comparison purposes, constructing a full generator using these modules is not necessary, and instead a single generator rig that assures consistency is used. The simple rig is similar to the one that shown as a half-section in Fig. 5. It consists of two aluminum plates for the hot side and cold side. Cooling is achieved independently by a 12 Vdc brushless fan blowing against the finned cold side. A thermostatically controlled hotplate is used to attain the hot side operating temperature. The same rig is used to test the two different modules successively with as much consistency as possible.

The procedure involves first heating to the maximum operating temperature. A rheostat is then used to simulate a varying load resistance in the appropriate range. Open circuit and short circuit conditions are first recorded. Load voltages and current histories of the modules are then acquired while taking into account the resistance of the measuring device. Fig. 7 shows the load power versus load resistance for both the HT6-12-40 and the TEC1-12708 modules. The figure shows the latter module to produce more power in general at all loads. This is expected since the latter module has shorter and broader thermoelements. The figure serves to provide the optimum load, and thus the internal resistance, for each type of module. While the

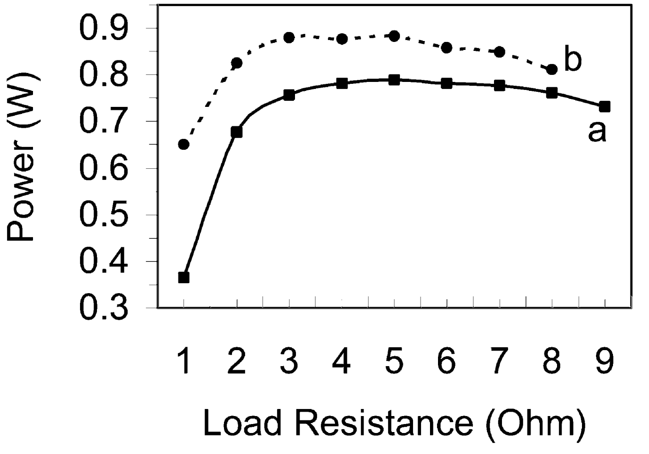

Figure 7. Achieved load power output from modules. (a) HT6-12-40 module with $\Delta T = 68$ K, (b) TEC1-12708 module with $\Delta T = 68$ K.

experiment performed on each module was kept as consistent as possible, errors in temperature measurement arise from imperfect thermocouple readings.

Considering the maximum power condition, theoretical estimates can be found from eq. (1) and/or (8). Using the specifications of each module, the MQF of each can be found from eq. (4) to be 0.654 for the HT6-12-40 module and 0.630 for the TEC1-12708 module (Table 2). The maximum power for module can then be given theoretically as:

$$P_{\max} = \begin{Bmatrix} 0.0756\alpha^2\sigma\Delta T^2, & \text{HT6-12-40} \\ 0.0785\alpha^2\sigma\Delta T^2, & \text{TEC1-12708} \end{Bmatrix} \tag{9}$$

This shows that, based on geometry and manufacturing quality, the TEC1-12708 module should produce 3.8% more power at matched load for similar material specifications and temperature differences. On the other hand, the Bi_2Te_3 specifications usually differ amongst manufacturers.

It is to be observed that due to non-perfect experimental conditions, it may be reasonable to expect better outputs from both modules. The obtained results seem

Table 2
Expected and measured MQF of two available modules

	HT6-12-40	TEC1-12708
$P_{\max}$ theory, ideal	0.810	1.025
$P_{\max}$ experiment	0.789	0.889
$P_{\max}$ / MQF	1.24	1.63
MQF, theory	0.653	0.630
MQF, experiment	0.636	0.546

to indicate that the MQF of both is lower than predicted by theory using the values assumed in section (eqs. (1) and (4)):

Contact losses may be responsible for the performance. For example the parameters r and n (in eq. (4)) which account for thermal and electrical contact resistance, may be higher than noted previously (i.e. they may be more like r= 0.25 and n= 0.15 mm). The possible difference in the B_2Te_3 properties of the two manufacturers has not been taken into account. This may have some effect on the power factor used but it is certainly not large in the current context. Experimental errors and other factors accounted for, the experiment does nevertheless confirm the expected higher output of the TEC1-12708 based on its shorter legs and wider thermoelements. Also apparent is that one can only expect just under one Watt for such modules under normal operating conditions (T_{Hmax} = 160 or a little less, with T_C around 70 °C). This leaves the door open for improvement of the contact/solder properties of modules of this type to enable it to work normally up to around 200 °C.

4.4. Re-designed high-temperature Peltier module

The high temperature Peltier module TEC1-12708 that was taken as the base case is re-designed in an attempt to maximize its power output without significantly departing from its basic design features. The temperature regime is still taken as before (T_H = 150 to 160 °C, ΔT = 100 K). The optimization is simple in that it involves simply shortening the Bi_2Te_3 pellet length while broadening its cross-sectional area together with requiring a minimum inter-leg clearance and overall module size. Table 3 below shows the details of this re-design. In principle, there should be little added manufacturing complexity to the standard case. The only alteration

Table 3
Comparison of high temperature Peltier module and its power-optimized simple re-designed version

	Standard TEC1-12708	Re-design - 1
Leg height, mm	1.2	1.1
Leg width, mm	1.4	1.6
Inter-leg spacing, mm	1.1	0.7
Area-to-length ratio, mm	1.63	2.33
Alumina wafer thickness, mm	0.63	0.63
Contact/solder thickness, mm	1.0	0.8-0.85
Total module height, mm	3.46	3.16-3.21
Couples per module, N	127	127
Module dimensions, mm x mm	40x40	40x40
Total thermoelement-to-module area ratio ($2NA/A_m$), ∗	0.31	0.41
Module volume, m^3	$5.536 x 10^{-3}$	$5.120 x 10^{-3}$
$P_{max}/\Delta T^2$, W/K^2	$2.4 x 10^{-4}$	$3.3 x 10^{-4}$
P'/volume, m^{-2}	19.45	28.45
Mass of Bi_2Te_3 in module, gm	4.48	5.36
P′/mass, m/gm	24.0	27.2

∗ A: single leg area, A_m: module area∗∗ Given by eq. (6), where the power factor is in W/mK^2

required to the process would be in the semiconductor wafer/pellet cutting stage and ceramic conducting strips.

Assuming a 100 K temperature difference, the maximum power generated in the standard TEC1-12708 design is found to be 2.40 W while for the new design Mk 1 it is expected to be 3.3 W — an increase of 37%. If the temperature difference could be raised, significant power output can be expected.

Considering the re-designed module and assuming a practical power output of about 2.7 W, the number of modules required for the 100 Watt design can be reduced to 36. The dimensions of the generator are over 32 cm x 20 cm (for an 8x5 module layout) which is considerably more compact than the standard case. The volume is now approximately 0.007 m^3 raising the power density to about 14 kWm^{-3}, which is a 40% improvement over the standard TEC1 module. Estimating the new Mk 1 design price to be around \$10 a module, the cost of the modules alone would now be around \$360 and the expected cost per watt is down to about \$4.5/Watt which represents a small but significant advance over the standard module.

Further progress could be made if the temperature difference could be increased to 120 K. Another advance could be in pushing the standard design to its limits by increasing the leg sizes and decreasing the inter-leg space further as has been previously discussed. Such a design could possibly reach a power density of about 22 kW/m^3 and reduce the cost to about \$3.5/Watt. Here practical limitations associated with the manufacturer limit the present study to the simple re-design discussed.

4.5. High-temperature type-I power modules

Previous studies on stove/waste heat generators have usually been based on lead telluride or so-called high-temperature Bi_2Te_3 power modules. These type-II modules should be in general geometrically better optimized for power production than Peltier type modules. They are bare, however, having no hot or cold side electrical insulating wafers. This leaves the problem of establishing good contact to the user and may lead to lower than expected output.

A typical module of this type, which is commercially available, is the Hi-Z Company's HZ-20 which is stated to approach 19 W maximum output with a ΔT of near 200 K. In general practice, such a ΔT is difficult to attain with simple air cooling and 100 K or little larger is more realistic leading to an output of less than half the stated maximum power. The module is large as seen from the previous tables, which affects the power density. The biggest disadvantage with this type of module is the high cost which stands at over \$200 per module.

A possible medium-range target in this work could be to design a module optimized for high power output but limited to a maximum input temperature of 160 °C and a ΔT of 100 K. Such a module could build on the previously discussed optimization of standard type-I Peltier modules. A target module size of 40 mmx40 mm square could be selected in the range 55 mm to 35 mm to be similar to Peltier modules' size. This small size is useful in comparative studies and may be useful in limiting stresses that may arise in larger modules' ceramic insulator plates. The inter-leg spacing may be reduced to 0.7 or 0.8 mm as a practical lower limit in order

to pack as much material as possible in the module. The optimum leg height is independent of the thermoelement leg width as long as a overall module size and inter-leg spacing has been chosen (see Figs. 2 and 3). For the above selection optimum power will occur at a leg height of 0.45 mm. The optimum power generated depends on the leg size square width selected as shown in Table 4 below.

It is seen that the ultimate the above module with the above dimensions and operating conditions could achieve is 8.25 W. This ultimate case corresponds to a single couple module that may not be appropriate noting the current and voltage output. Modules with standard Peltier cooling type leg sizes (around 1.4 mm), even if with legs reduced in height to optimum, can only produce 48% of the full potential power. Similar calculation could be made for other module sizes but that is of no special value here.

Too few thermoelements leads to unreasonable output features of large current and very small voltage. On the other hand, designs with too many thermoelements means small leg sizes (for a given module size) or large modules and more manufacturing complexity. In this work, a proposed compromise could be introduced which may involve a module with 25 couples where each leg has a width of 5 mm (keeping module size and inter-leg spacing fixed). This design is seen to produce about 7 W. In general a small change in inter-leg spacing (i.e. increase from 0.7 to about 0.9) has little effect on the performance especially for the large leg size designs. If the 0.45 mm leg height is too small and may create manufacturing or heat-leak problems then a relaxation to about 0.55 mm would cause the power to drop to about 6.5 W.

The 6.5 W design here is considered the most practically achievable, the amount of Bi_2Te_3 in this module is about 15% more than in a standard TEC1-12708 Peltier module. The price of a module may be expected to rise by about the same amount since the manufacturing process is the same. For a 100 Watt application, 15 modules are required. At about \$9.5 a module, and adding 25% for manufacturing the generator gives around \$1.8/Watt which is a ten-fold improvement over certain Peltier modules used in the power generating mode.

Regretfully, though such a module is still costly. The design is still taken as a

Table 4
40mmx40mm module, a=0.7, ΔT=100 K, Lopt=0.45 mm

Leg width, x [mm]	Max. packed couples, N	Max. current, I [A]	Max. voltage, V [V]	Maximum power, [W]	% of ultimate power
18	1	280.5	0.030	8.25	100
9	9	70.14	0.109	7.64	93
6	18	31.17	0.229	7.13	86
5	25	21.65	0.316	6.84	83
4	36	13.85	0.465	6.44	78
3	58	7.790	0.751	5.85	71
2	109	3.464	1.411	4.89	59
1.6	151	2.216	1.944	4.31	52
1.4	181	1.697	2.332	3.95	48

current design goal and further work is currently in progress using a slightly downgraded design version.

5. Concluding remarks

A thermoelecric generator for stove-tops has been studied. In an environment of intermittent and uncertain electric supply this makes sense and a potential market exists. The generator design work has used existent high-quality Peltier modules in the power-generating mode and has demonstrated acceptable economic performance. As a further development, the adaptation of Peltier-type modules to the temperature regime at hand led to a new design of module optimized for maximum achievable power while keeping cost down.

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